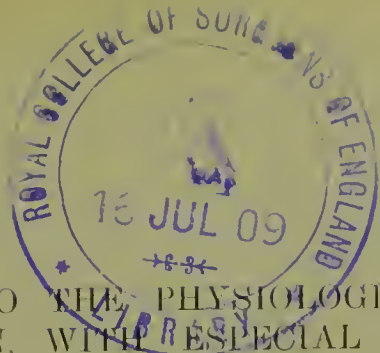FROM THE

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AN INQUIRY INTO THE PHYSIOLOGICAL MECHANISM OF RESPIRATION, WITH ESPECIAL REFERENCE TO THE MOVEMENTS OF THE VERTEBRAL COLUMN AND DIAPHRAGM.[1] By J. F. Halls Dally, M.A., M.D. Cantab.

Introductory.

In studying the alterations which occur in the shape, size, and position of the internal organs as a result of their functional activity, previous observers have worked at a disadvantage.

Previous knowledge, gained directly from man, is based chiefly on the results of anatomy, physiology, pathology, and surgery.

Reconstruction of life-changes from dissections and histological preparations is limited, although inferences as to function can be drawn from the structure and disposition of the viscera.

Changes in the contour of trunk and limbs have been estimated by means of various instruments, e.g. oncometer, stethometer: shadow-lines have been observed, e.g. Litten's diaphragm phenomenon: and variations in function have been studied after inhalation of mixtures of gases, e.g. anæsthesia. Physico-physiological experiments, too, are useful, e.g. volumetrically, in measuring the vital capacity of the lungs.

From the results of the preceding methods, vital processes, and changes which the internal organs undergo, can only be inferred. During the past nine years changes in size and position of the thoracic contents have been studied carefully by means of watching their moving shadows on the Röntgen screen. X-ray methods, though indicating an advance in our knowledge of abdominal and thoracic visceral movements, have not been of absolute utility, owing to the fact that the rays proceeding from the fluorescent tube, being divergent, produce magnification of the shadow of the object proportional to the respective distance of the latter from tube and screen. Hence it has been impossible to obtain mathematically exact measurements.

The Scope of the Present Research.

The present research deals solely with the physiological mechanism of respiration, the preceding methods being utilised only in so far as they are necessary to supplement and confirm the main evidence which has been

[1] A summary of the chief results of this investigation is embodied in a paper read before the Royal Society, Feb. 6, 1908, and published in the *Proceedings of the Royal Society*, B, vol. lxxx., 1908.

derived from the use of an instrument called the orthodiagraph, of which a detailed description has already been published.[1]

By means of this instrument it is possible, with almost mathematical accuracy, to measure motionless objects which lie in a plane parallel with the

FIG. 1.

vertical transverse plane of the body, and to measure moving objects with greater approximation to exactitude than can be attained in any other manner.

The explanation is as follows :—

In a fluorescent tube, when the electrons shot off from the kathode suddenly are intercepted by the antikathode, they set up electric vibrations in the ether precisely similar to those of light, save that their wavelengths are much shorter. By cutting off all the rays projected from the antikathode, with the exception of the central pencil, and by conducting this latter round the shadow-margin of an organ, irrespectively of the

[1] *British Medical Journal*, Sept. 14, 1907, p. 651.

greater or less magnification of the shadow on the screen, a record can be traced which represents the actual size of the object examined.

In order to find out how closely one can measure, a series of experiments was undertaken, two of which are here recorded :—

Experiment I.—A brass quadrant was placed between the leaves of a book 10 centimetres distant from the surface of the book nearest to the fluorescent tube, so as to imitate the density of the tissues of the body. Orthodiagraphic measurement was then made, and the resultant tracing was found to correspond closely with the original.

Experiment II.—A similar experiment was performed with a metal ring (fig. 1, *a*), the resulting circle of dots corresponding with great exactitude to the outline of the original (fig. 1, *b*).

I propose to consider the subject under the following heads :—

    I. Results obtained by Orthodiagraphic Measurement of Changes in the Trunk which occur during Respiration.

    II. The Movement of the Vertebral Column in Respiration.

    III. Anatomical Dissimilarity of the Two Halves of the Diaphragm.

    IV. The Means by which the Diaphragm is supported.

    V. The Level of the Diaphragm—

        1. After death.

        2. During life $\begin{cases} \text{at rest.} \\ \text{in action.} \end{cases}$

    VI. The Range of Movement of the Diaphragm.

    VII. The Costo-phrenic Pleural Reflexion.

    VIII. Age-changes in the Thorax and Diaphragm.

I. Results obtained by Orthodiagraphic Measurement of Changes in the Trunk which occur during Deepest Possible Respiration.

The average changes which occur during inspiration in a series of one hundred healthy subjects, of ages varying between 15 and 35, are recorded as follows :—

(1) The neck is shortened 10 mm., and widened on the right side 9 mm., on the left side 7 mm.

(2) The shoulders are raised on the right side to a slightly greater extent than on the left, the average on the right being 16 mm., that on the left 14 mm.

(3) The presternum moves 30 mm. in an upward, and 14 mm. in a forward diameter.

(4) The clavicles execute a combined upward, forward, and outward movement, the vertical range of their inner ends on the right side being

28 mm., on the left side 27 mm.; of their outer ends, on the right side 21 mm., on the left side 16 mm. The divergence from the median line is, on the right side 7 mm., on the left side 6 mm.
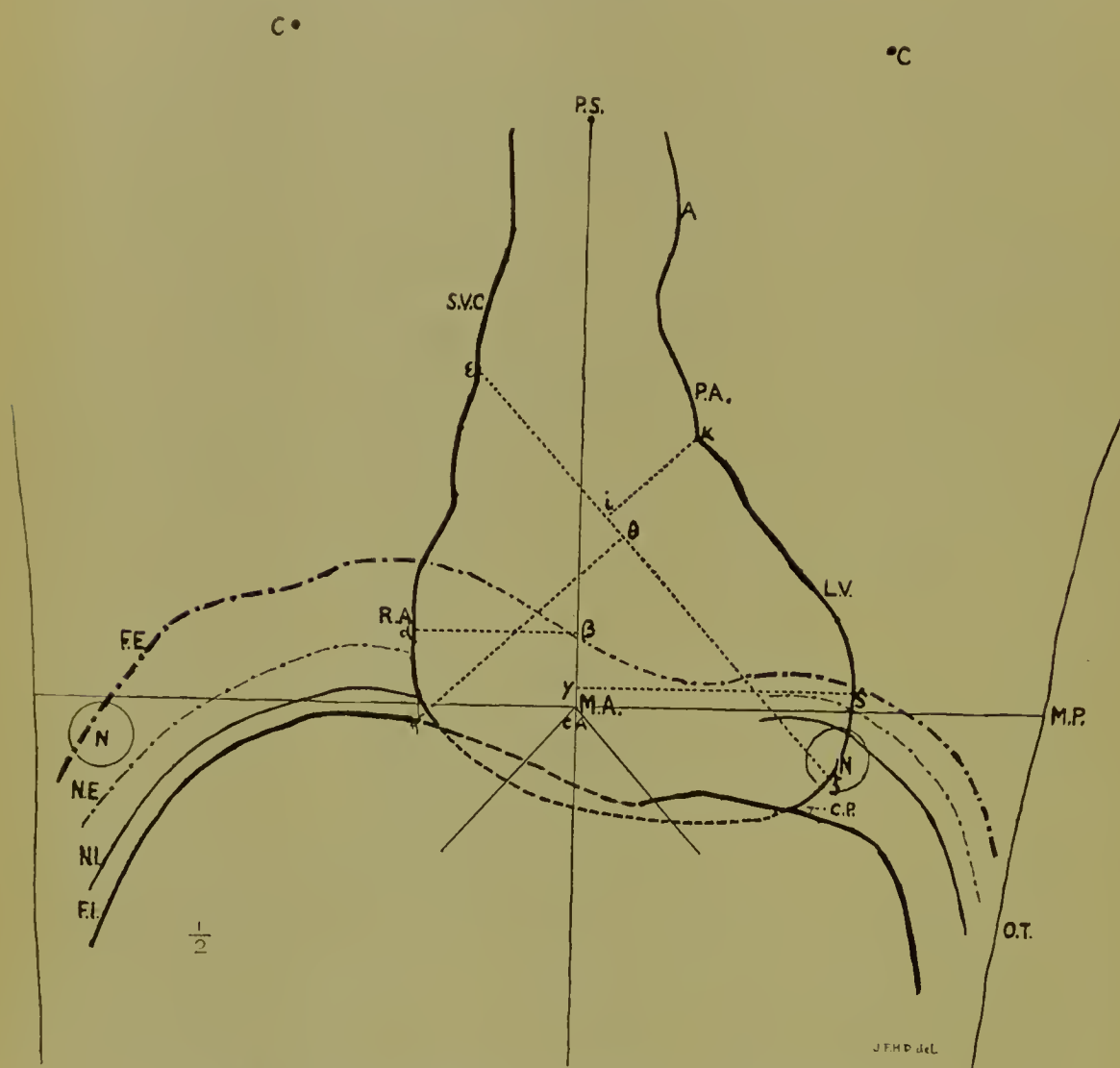
FIG. 3.— Orthodiagram No. II. Subject in antero-posterior position.

(5) The meso-metasternal articulation either may remain in the same horizontal plane, or may rise as much as 46 mm. The average ascent is 28 mm.

(6) Widening of the infracostal angle occurs, the interval between the costal margins, measured on each side at a level of 30 mm. below the meso-metasternal articulation, being increased by 26 mm.

FIG. 2.—Orthodiagram No. I.   Subject in antero-posterior position.

C.   Mid-clavicular point.
P.S.   Presternal notch.
S.V.C. Superior vena cava.
R.A.   Right auricle.
A.   Aortic arch and first portion of descending aorta.
P.A.   Left pulmonary artery.
L.V.   Left ventricle.
P.   Pericardium and plicæ adiposæ.
P₁.   Pericardium.
αβ.   Diameter of right auricle.
εξ.   Diameter of left ventricle.
ηθ+ικ. Longitudinal diameter of heart.
        Diameter of right ventricle.

N.   Nipple.
U.   Umbilicus.
F.E.   Forced expiration.
N.E.   Normal expiration.
N.I.   Normal inspiration.
F.I.   Forced inspiration.
M.A.   Meso-metasternal articulation.
M.P.   Meso-metasternal plane.
O.T.   Outline of trunk.
C.A.   Infracostal angle.
C.P.   Cardio phrenic space.

Position of diaphragm in.

(For description of which v. The Lancet,
June 27, 1903, p. 1802.)

(7) The trunk is widened at the level of the meso-metasternal plane 9 mm. on the right side and 8 mm. on the left, and midway between the meso-metasternal plane and lowest point of the costal margin, 9 mm. on the right side and 11 mm. on the left.

(8) The umbilicus is retracted and drawn upwards in deep respiration for a distance of 13 mm., on account of the active recession of the abdominal wall produced by the contraction of the abdominal muscles, which, in this phase of respiration, act as antagonists of the spinal muscles. The upward displacement of the umbilicus is usually to the right, but may be median or to the left, the lateral deviation being 7 mm.

(9) The heart and pericardium together undergo important changes in size and position as a result of the respiratory movements, being considerably lengthened and narrowed in inspiration, and shortened and widened during expiration.

(10) The pericardium, at the level of its attachment to the central tendon of the diaphragm, in the adult measures 80 mm. in antero-posterior diameter.

Fig. 2, orthodiagram No. I., of the chest of a healthy male aged 20, forms a typical example of most of the above-mentioned movements.

NOTE.—*In orthodiagrams Nos. II. and III. the same lettering is used as in orthodiagram No I., and in all of them the position in inspiration is indicated by a heavy continuous line, and the position of expiration by a heavy broken line.*

Fig. 3, orthodiagram No. II., of a female aged 13, exhibits good range of diaphragmatic movement.

II. THE MOVEMENT OF THE VERTEBRAL COLUMN IN RESPIRATION.

The movement executed by the spinal column in respiration is an important one, and has been ignored.[1] I can find no reference thereto in any of the eight latest and best-known text-books of physiology published in this country. That this movement is actual and of mechanical advantage in breathing can be verified by visual and orthodiagraphic examination.

1. *Visual Examination.*

(*a*) *In the upright lateral position* the respiratory spinal movement becomes most evident if a succession of deep respirations be taken. On inspiration the shoulders are squared and the head elevated and thrown backwards, then there is a gradual backward movement of the whole

[1] Many anatomical teachers have been in the habit of teaching and demonstrating the spinal movements in connection with the respiratory act. [D. J. C., Acting Ed.]
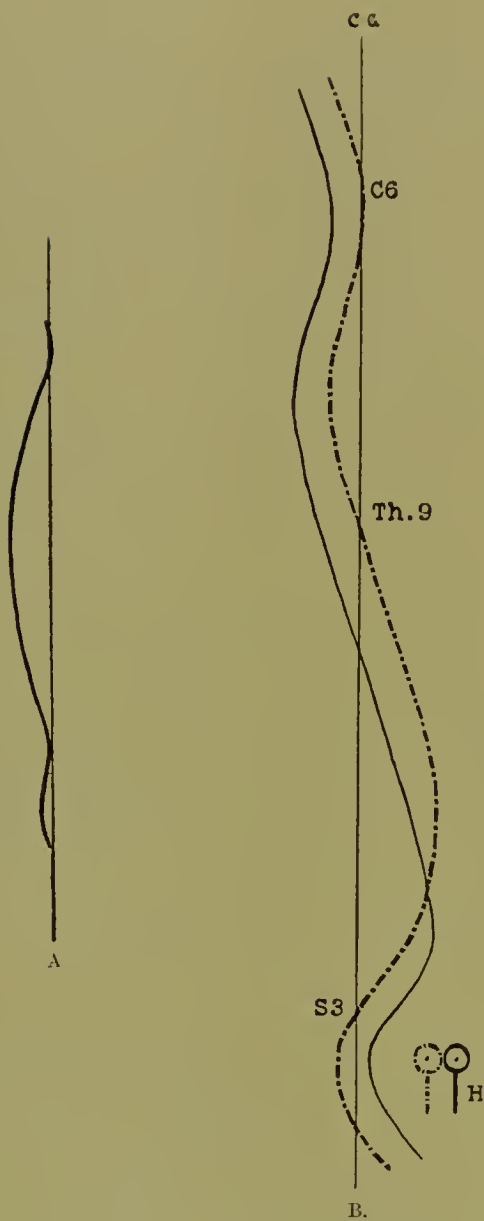
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FIG. 4.—A, Vertebral column of fœtus (koilo-rachic). B, Vertebral column of adult (kurto-rachic). The diagram on the right shows the position of the vertebral column in inspiration (continuous line) and expiration (broken line).

C6. sixth cervical vertebra; Th.9, ninth thoracic vertebra; S3, third sacral vertebra; C.G., centre of gravity; H., hip-joint.

thoracic spine with simultaneous extension of the upper thoracic vertebræ as far as the superior scapular angle, in consequence of which in deep breathing the upper thoracic region is widened antero-posteriorly. When

respiration becomes profound, and the upper half of the spine is relatively much displaced backwards, the shifting of the centre of gravity is compensated for by a forward movement at the hip-joint, which has the effect of throwing forward the sacrum and lower lumbar spine (fig. 4). Less intense respiration produces correspondingly less effect, and in quiet breathing no forward movement at the hip-joint is necessary. The throwing backwards and fixation of the head and shoulders, together with the forward tilting of the pelvis, affords the greatest opportunity for unimpeded and deep breathing, and this position instinctively is assumed by those whose pursuits necessitate maximum aeration of the lungs, *e.g.* in running. This attitude also is most effective for voice-production, since not only does maximum expansion of the upper part of the thorax allow of large intake and storage of air, but the thorax in its capacity as resonator is brought as near as possible to the vocal cords (Campbell).

(*b*) *In the upright posterior position* the spinous processes appear to move beneath the skin, downwards on inspiration and upwards on expiration, this effect being very noticeable in thin people when they respire deeply. A small proportion of this inspiratory downward movement is a true one, due to the extension of the vertebral column, but the remainder of it is caused by the skin being drawn upwards over the spinous processes owing to raising of the shoulders.

2. *Orthodiagraphic Examination.*

The shadow of the vertebral column is seen clearly separated off from that of the pericardium and great vessels by a transradiant triangle,[1] the base of which is formed by the upper surface of the diaphragm. On inspiration the posterior wall of this triangle formed by the spinal column is seen to recede, to a greater extent below than above, and so to open out the interval from before backwards. With subsequent expiration the spine advances.

Fig. 5, orthodiagram No. III., shows plainly the movement of the diaphragm between deep inspiration and expiration, the range of the vertebral column (V.), the contour of the heart and of the liver (L.).

Explanation of the Spinal Respiratory Movement.

A general rectification of the curvature of the thoracic portion of the vertebral column takes place. In a series of eight orthodiagraphic observations upon healthy adults of both sexes, I found that the average antero-posterior range of spinal movement was as follows:—

At upper aperture of thorax, opposite first thoracic vertebra, 6 mm.

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[1] *The Lancet,* July 11, 1903, p. 125.

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Midway between upper aperture of thorax and level of diaphragm, in deep inspiration, opposite fifth thoracic vertebra, 7·5 mm.
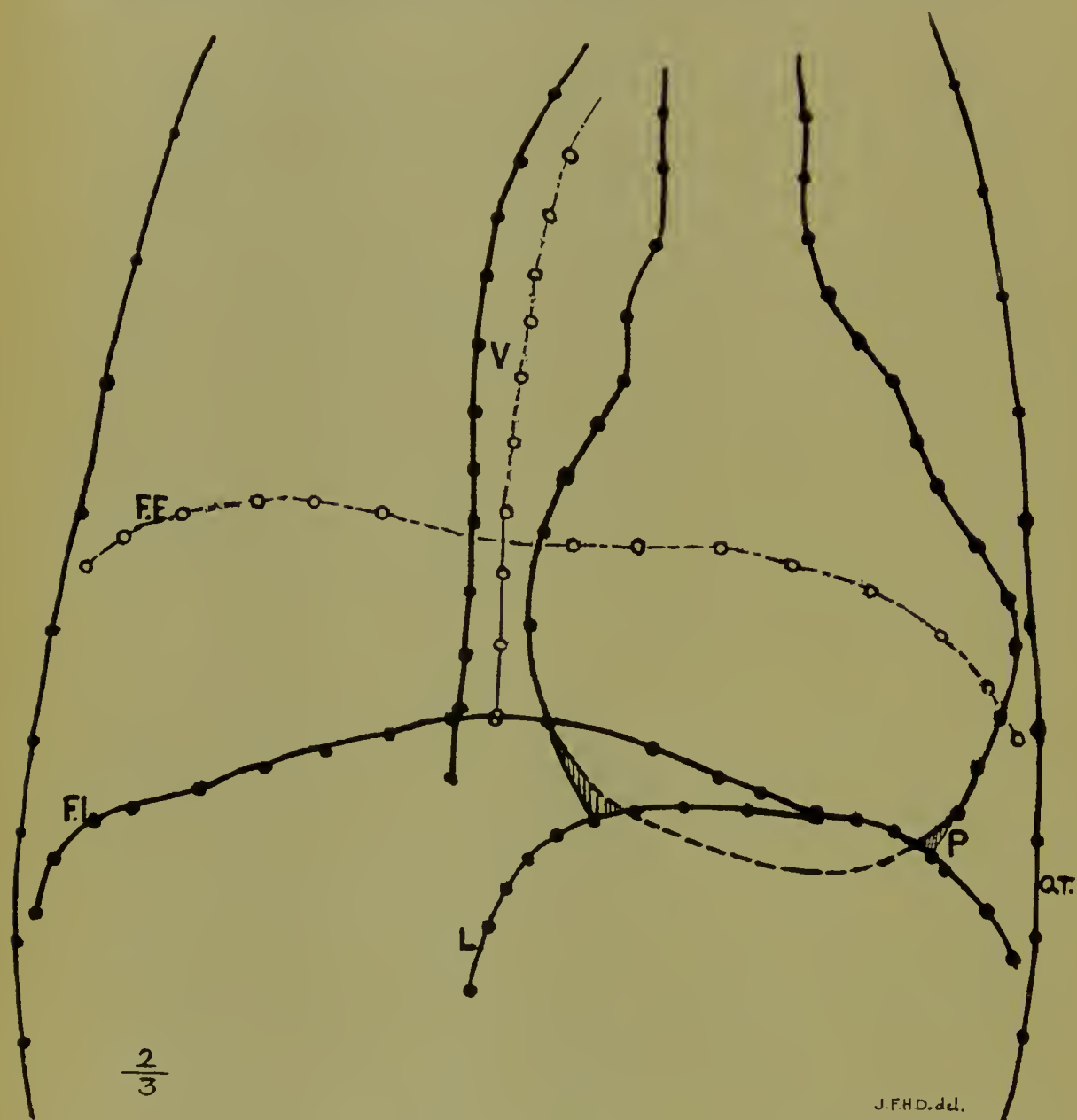

FIG. 5.—Orthodiagram No. III.   Subject in lateral oblique position.

At level of posterior part of diaphragm, in deep inspiration, opposite tenth thoracic vertebra, 9 mm.

These measurements show that on the average the spinal column is most displaced towards the lower part of the thoracic curvature, and that

rectification lessens from below upwards. Individual differences, however, are not infrequent. The straightening out of the thoracic curve, which occurs especially in that segment of the spine which articulates with the sixth, seventh, eighth, and ninth ribs, is due to contraction of the erector spinæ muscle which produces backward extension of the vertebral column, whilst at the same time the sternum is raised upwards and forwards by contraction of the cervical and thoracic elevator muscles, thus bringing a larger costal arc into the place previously occupied by a smaller one, and so increasing the antero-posterior diameter of the thorax. Upon the ribs assuming a position of less obliquity, the spinal column, being far more limited in its possible range of movement than the sternum, on account of its multiple attachments, can only execute a fraction of the sternal movement. Towards the end of inspiration, as the movement of the sternum reaches its dynamic limit, the remainder of the force of the respiratory cycle is spent upon the spine, which accordingly, during the latter half of inspiration, shows progressive mobility.

In inspiration the spinous processes are approximated and closely overlap, thus forming a natural protection against hyper-extension of the vertebral column and consequent injury to the cord. The bodies of the vertebræ show slight divergence anteriorly in consequence of the opening-out of the intervertebral discs, and the anterior common ligament is made taut. Correspondingly, the ribs are separated, and so the chest is enlarged in forward, outward, and upward diameters. In expiration the reverse takes place; the spinous processes separate, the bodies are approximated anteriorly, and the ribs are brought much nearer to each other.

Measurement of the Spinal Movement.

The spinal movement is best estimated by means of the orthodiagraph. The subject is turned into the right or left lateral oblique position until the maximum area of transradiance and the greatest amount of luminosity are obtained between the shadow of the vertebral column behind and of the aorta in front. This involves a rotation through an angle of from 30 to 45 degrees. The shadow of the vertebral column forming the posterior boundary of the interval is then seen to move backwards and forwards rhythmically with respiration, the apparent movement being from 6 to 9 mm. Owing to the obliquity with which the normal incident pencil of rays strikes the anterior surface of the spine, the real movement in this instance is larger than the indicated movement. The exact amount of movement which the spine has undergone readily can be calculated as follows:—Suppose the anterior surface of the vertebral column to be at a.

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The central pencil of rays coming from the tube at o will cut the anterior surface of the vertebral column at a, and will impinge upon the screen at b. If now the vertebral column moves from a to a', the shadow will move along the screen to b'. If the angle between the screen and the line joining a to a' is θ, then

$$a\,a' \cos \theta = b\,b',$$

therefore

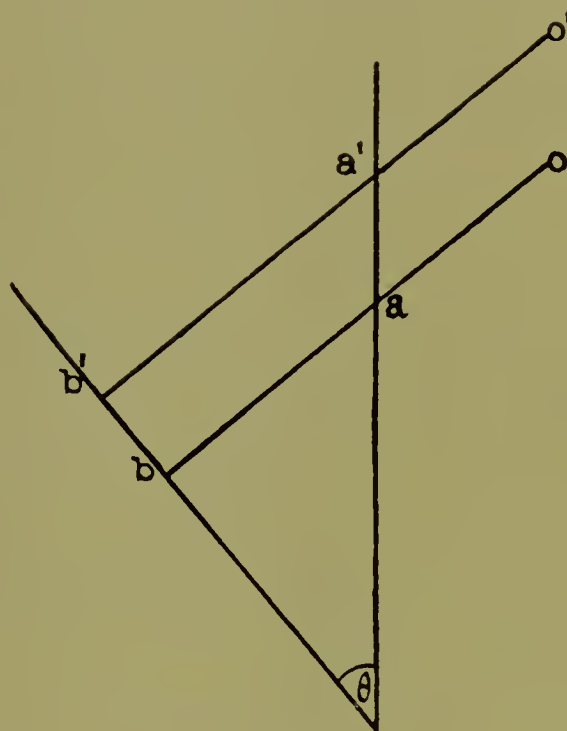$$a\,a' = \frac{b\,b}{\cos \theta}.$$

Fig. 6.

It is necessary, therefore, to measure $b\,b'$ and θ, whence the true amount of spinal movement can be determined by the above formula.

Importance of the Spinal Movement.

The antero-posterior enlargement of the thoracic cavity produced by simultaneous extension of the thoracic vertebræ when deep breaths are taken, has an important influence upon the aeration of the apices of the lungs, the forward and upward movement of the thorax, together with the backward movement of the vertebral column, being of far greater value than the lateral movement in promoting free access of air by assisting the action of the diaphragm.

Morphological Note.

On account of "meristic variation" (Bateson), the spinal segments are not comparable in number among the Vertebratæ, the early vertebrate body being lengthened in order that mobility should be increased. The spinal column of the fœtus and of the young child in type approximates to the simple form found amongst the anthropoid Cercopithecidæ, and exhibits only rudiments of the compensatory curves later to be developed as a result of the assumption of the erect posture (fig. 4, A).

III. Anatomical Dissimilarity of the Two Halves of the Diaphragm.

Anatomically the two halves of the diaphragm differ in size and shape. The right half is the larger, and the corresponding portion of the central tendon is bigger than the middle or left portions. The right vault stands at a higher level than the left, which latter is depressed and flattened by the superincumbent weight of the heart. One-third of the plateau on which the heart rests is situate to the right of the middle line, and two-thirds to the left. The arch on the left side rises from the central tendon more abruptly than on the right side, and to a much less extent. Its descent also is more sudden, so that the curve is flatter, and may be represented by an arc of a circle, the centre of which is situate on the seventh left costal cartilage, and whose chord-base is directed obliquely downwards, the lower extremity being further from the median line than the upper extremity, ending above at the lowest point of the fifth costal cartilage and below at the lower border of the eighth rib, a little external to the costo-chondral junction. If the chord-base be bisected, and a perpendicular be let fall upon it, this perpendicular will cut the mid-point of the arc, and, if further produced, will touch the region of the left axilla. In expiration the anterior part of the right side of the diaphragm is placed at the highest level; on the left side the mid-portion of the curve takes the highest position. The rounded contour is maintained by the negative intra-thoracic suction and the positive intra-abdominal pressure, both of which act, the former to the greater extent, in producing a constant tendency to ascent of the diaphragm within the cavity of the thorax. The right crus is far stronger than the left, and has more extensive attachments above than below. It is more median in position than the left crus, and the fibrous band stretched over the aorta, directly continuous with the tendon of origin of the right crus, serves as a basis of support for the main part of the median strong muscular fibres which encircle the œsophagus and pull down-

wards and forwards the posterior part of the central tendon, pericardium, and roots of the lungs. The costo-sternal muscle-fibres are usually better developed on the right, and enter into more forcible action, the reason being that this half has to overcome the resistance of the large mass of the liver, whereas the stomach is much more easily compressed by the left half. So that, functionally, although the two halves of the diaphragm are of unequal size and strength, yet, owing to the difference in resistance on the two sides, their range of movement is but little dissimilar, the difference, if present, being usually in favour of the right half.

IV. THE MEANS BY WHICH THE DIAPHRAGM IS SUPPORTED.

The supports of the diaphragm are :—
  A. Superior or thoracic.
  B. Inferior or abdominal.

A. *The superior supports* consist of (1) the dense inelastic outer layer of the pericardium, firmly united at its base with the upper surface of the diaphragm, and prolonged into (2) the sheaths of the great vessels, which in turn become blended with (3) the middle and anterior layers of the cervical fascia. Through the medium of the latter the diaphragm is slung from the skull, hyoid bone, and thyroid cartilage, sternum, and clavicles. It is also slung from the sternum by (4) the upper and lower sterno-pericardial ligaments, and from the vertebral column by (5) the prevertebral layer of the cervical fascia medially blending with the anterior common ligament of the diaphragm, whilst laterally it gives rise to strong and scattered fibrous bands which descend through the superior mediastinum and in front of the roots of the lungs to be continued on the side of the pericardium as the *ligamenta suspensoria* of the diaphragm. (6) The upward suction action of the lungs has also an important influence. (7) The right or lateral fornix of the inferior vena cava is firmly fixed to the central tendon, and through this indirectly to the right crus, whilst (8) the posterior pericardial wall links the lateral fornix of the inferior vena cava to the corresponding fornix of the superior vena cava, which in turn is joined to the pulmonary root, and, above this, by a fascial continuation, to the superior aperture of the thorax. Hence, by its superior ligaments, the diaphragm is slung from skull, spine, and sternum, and, through the medium of the middle cervical aponeurosis, from all the additional bony points at the upper aperture of the thorax which are capable of affording a surface of implantation.

B. *The inferior supports* consist of (1) the liver and its ligaments, (2) the inferior vena cava, a very powerful support, (3) the stomach and

intestines ("air-cushion"), themselves retained in position by (4) tonic contraction of the muscles of the anterior abdominal wall.

V. THE LEVEL OF THE DIAPHRAGM.

1. *After Death.*—In order to ascertain the "level" of the diaphragm in man, in the first place it is necessary clearly to understand what this term implies. After death the position of the diaphragm, then simplest to verify on account of its immobility and ease of access, indicates only one phase of respiration; during life, on the other hand, the level rises or falls with each stage of the respiratory cycle. The resting period occurs at the end of moderate expiration, and the position which the diaphragm consequently assumes is most conveniently taken as its level during life. Deep expiration is the terminal act of life: so that when the contraction effect of rigor mortis has passed away, the diaphragm is found in a position of complete expiration, being, in other words, thrust up by positive intra-abdominal pressure and drawn up by negative intra-thoracic suction. Manometric observations easily prove that, after death, these pressures exist, and the speedy return of the lungs to the *status quo ante* after artificial distension within reasonable limits, shows that death does not limit elasticity, at all events for some hours. Hence we see that the level of the diaphragm post-mortem is not quite the same as the level intra-vitam, but a little lower.

From the results of an examination of eighty dissecting-room and post-mortem-room cases, I find that the average highest point of the dome of the diaphragm in the cadaveric position is situate, on the right side, at the level of the upper border of the fifth rib in the mid-clavicular line; on the left side, in the mid-clavicular line at the lower border of the fifth rib. This corresponds with the results of orthodiagraphic measurement in bodies of healthy persons who have met with sudden death.

2. *During Life.*—Arguments from the pathological to the physiological being often fallacious, deductions as to the level of the diaphragm, based merely on statistics from the post-mortem and dissecting-rooms, when applied directly to the healthy living subject, are liable to mislead. The average level of the diaphragm, calculated for healthy living people, probably should be higher than the level given above, since in the majority of dissecting-room bodies, owing to atrophy of muscle fibre and laxity of ligamentous attachment accompanying advancing years, the diaphragm stands at a lower level than it ought. Although some diseases raise the diaphragm, most diseases lower it: hence it is most likely that, for pathological states also, the balance is struck too low.

Whilst it is true that, by inspection and percussion, we can map out a line on the surface of the thorax which corresponds approximately to the margin of the diaphragm, no further information is at our disposal relative to the contour of the domes and the level of these and of the central tendon. Orthodiagraphy here is of great service, in that it renders visible and measurable the rise and fall of the diaphragm, and the exact level which it attains in different phases of the respiratory cycle.

(*a*) *At Rest.*—The dome of the diaphragm rises a little higher on the right side than on the left. In the fœtus the dome usually is on a level with the fourth rib or interspace; in young infants its level is anywhere between the fourth and seventh ribs: in children it stands about opposite the fifth rib. In moderate expiration in a healthy adult the average position assumed by the highest point of the dome on the right side is opposite the level of the fourth intercostal space, or, less frequently, a little internal to the junction of the fourth rib with its cartilage, this being also the surface-marking for the right lobe of the liver; on the left side the average highest point is on a level with the upper border of the fifth rib at its costo-cartilaginous junction, which point also marks the position of the fundus of the stomach, or, if the stomach is contracted, the upper limit of the trans-verse colon. If the level is taken in terms of spinous processes, the right dome is found most often between the seventh and eighth, the left summit between the eighth and ninth, whilst the central tendon lies a little above the tip of the eighth. Posteriorly the lower edge of the diaphragm is situated on each side at the level of the twelfth thoracic spine. Anteriorly the level of the central tendon corresponds with the meso-metasternal articulation or is slightly above it, according as to whether the diaphragm is highly arched or not, whilst posteriorly it is opposite the body of the eighth thoracic vertebra.

The level of the diaphragm in its passive state, and to some extent in its active state, is influenced by the state of fulness or emptiness of the intra-abdominal viscera, and is raised or lowered accordingly. Gastric distension can produce a considerable rise in level on the left side. Lessening of the content of blood in the thorax also is said to cause elevation of the diaphragm.

(*b*) *In Action.*—Notwithstanding that the level of the diaphragm during life conveniently may be taken as that which is assumed during the resting period, yet, for more detailed research into the causes which limit diaphragmatic action, it is necessary to record the exact height of the domes and central tendon in the four phases of moderate and deep inspiration and moderate and deep expiration. Although, to some extent, these levels can be inferred from inspection, palpation, and percussion, of which

the latter is most helpful, and the position of the diaphragm deduced from a delimitation of the lower limits of lungs and heart and upper border of liver, spleen, and stomach, yet the inference lacks the scientific exactitude which is essential for the determination of slight variations from the normal, mainly because little more than the margin of the diaphragm can be mapped out by these methods, whilst the position of the domes is a matter of conjecture. Orthodiagraphic measurements, however, supply the precise information required concerning each portion of the moving or resting diaphragm, and, as a result of examination of the subject in various positions, one is enabled to obtain a composite clinical picture.

In attempting to ascertain the level in action, it is advisable to take some landmark as a point from which to measure, the position of which as nearly as possible corresponds with the mean average cadaveric position. The variability in position of the costal arches renders these unsuitable as a basis for visceral surface-markings. Indeed, in individuals of the same sex and age, the width of the ribs and cartilages and of the intercostal spaces may differ considerably, and, moreover, may be relatively unequal on the two sides. The nipple-level is still more unreliable. Although the meso-metasternal sutural line, i.e. the junction between gladiolus and ensiform cartilage, presents slight changes in level according to age and sex, yet it meets the above-mentioned conditions, and forms a much more constant point from which to measure, since, in the European adult, the combined pre-mesosternum is not liable to much individual variation in length. Hence I have adopted the meso-metasternal articulation as the basis from which to measure, and the line drawn horizontally through this point —the meso-metasternal plane—as the plane to which the level of the rise and fall of the diaphragm of each side may be referred, and all orthodiagraphic measurements of the position of the domes and central tendon have been taken in millimetres above and below the level of this plane in preference to other and more usual landmarks.

VI. THE ABSOLUTE RANGE OF MOVEMENT OF THE DIAPHRAGM.

The absolute range of movement of the diaphragm between deep inspiration and deep expiration in the adult male is, on the right side 34 mm., on the left side 32 mm. The range in adult females amounts to 27 mm. on the right side and 25 mm. on the left side, making the total average range 30 mm. on the right side and 28 mm. on the left. Up to now the excursion of the diaphragm has been stated at about double the above figures, this being due to the fact that, until the introduction of the

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TABLE 1.—Distance in millimetres of the highest point of the diaphragm above or below the level of the meso-metasternal plane in the position of rest, measured at a point midway between the vertical median line and the lateral wall of the trunk.

The + prefix indicates the distance above the meso-metasternal plane, the − prefix the distance below.

		Right side.				Left side.			
No.	Age.	Max. exp.	Max. insp.	Norm. exp.	Norm. insp.	Max. exp.	Max. insp.	Norm. exp.	Norm. insp.
		Healthy Males.							
1	17	− 70	− 25	− 25	− 37	− 34	− 44	− 53	− 37
2	41	− 16	− 28	− 33	− 46	− 18	− 43	− 43	− 57
3	22	+ 6	− 33	− 25	− 41	− 7	− 50	− 30	− 48
4	20	+ 5	− 42	− 33	− 41	− 2	− 34	− 26	− 42
5	8	+53	+31	+36	+23	+31	+10	+14	− 6
6	19	− 7	− 32	− 21	− 33	− 3	− 36	−20	− 32
7	16	+58	+56	+46	+32	+48	+46	+37	+17
8	8	+16	+10	− 12	− 22	+ 4	− 5	− 21	− 33
9	19	+43	+ 8	+26	+ 4	+43	+11	+31	+13
10	26	+17	− 8	− 12	− 21	+ 9	− 41	− 40	− 55
11	60	± 0	− 46	3 −	− 9	− 17	− 53	− 42	− 47
12	20	+ 3	− 24	...	...	− 6	− 38	...	...
13	35	+36	− 19	+ 7	+24	+24	− 29	+12	− 29
14	23	+42	+10	+ 4	+25	+23	− 3	+ 6	− 12
15	13	− 9	− 30	− 37	− 40	− 11	− 28	− 35	− 42
		Healthy Females.							
16	30	− 16	− 17	− 22	− 29	+ 3	− 30	− 15	− 20
17	17	− 9	− 31	− 21	− 26	− 29	− 36	− 36	− 40
18	21	− 13	− 17	− 24	− 29	− 17	− 25	− 16	− 14
19	17	+ 2	− 2	− 1	− 4	− 21	− 28	− 21	− 27
20	18	+ 2	− 26	− 20	− 21	− 3	− 26	− 11	− 12
21	24	+31	− 2	± 0	− 9	+ 9	− 23	− 11	− 19
22	26	+33	− 9	+ 6	− 10	+10	− 17	+ 5	− 24
23	16	+36	+12	+13	− 22	+ 4	− 19	− 5	− 18
24	24	+ 4	− 26	− 19	− 25	− 14	− 10	− 45	− 50
25	20	+18	− 32	− 18	− 30	+ 6	− 37	− 22	- 36
26	22	+11	− 8	+11	− 2	+ 7	− 11	− 1	− 9
27	17	+ 8	− 15	− 9	− 25	− 17	− 42	− 33	− 53
28	13	+ 4	− 5	− 4	− 9	+ 4	− 18	− 15	− 23
29	17	+21	+16	+19	+10	+ 2	− 9	− 6	− 4
30	21	+17	− 15	− 12	− 26	− 2	− 30	− 29	− 40

orthodiagraph, by which the exact range of movement is recorded, it has been impossible accurately to allow for X-ray shadow-magnification. In quiet respiration the experimental error in the estimation of the range of movement has been much less, owing to the movement being but slight. In adult males the diaphragm in quiet respiration moves 16 mm. on the right side and 14 mm. on the left side; in adult females 9 mm. on the right side and 10 mm. on the left; whilst the total average movement is 12·5 mm. on the right side and 12 mm. on the left. From these figures we see that the movement in quiet respiration is approximately equal on the two sides, whilst in deep breathing the excursion is, for most people, slightly greater on the right side than on the left. In diagnosis the movement in deep respiration is the important one to observe.

TABLE II., showing in millimetres the absolute descent of the central tendon in a series of ten cases orthodiagraphically examined in the right anterior oblique position.

Sex.	Age.	Descent at posterior border of pericardium.	Descent midway between anterior and posterior borders of pericardium.	Descent at anterior border of pericardium.
		mm.	mm.	mm.
M.	25	26	30	25
M.	14	4	15	7
M.	8	11	7	6
M.	19	35	36	28
F.	19	11	16	12
F.	22	12	18	15
F.	20	32	42	35
F.	22	12	7	6
F.	13	16	15	14
F.	17	31	25	22
Total average descent		19 mm.	21·0 mm.	17 mm.

More extended observations confirm the above results, and show that the average descent of the central tendon of the diaphragm is 19 mm., its movement being greatest midway between anterior and posterior borders of pericardium, intermediate at the posterior border, and least at the anterior border of the pericardium.

VII. The Costo-phrenic Pleural Reflexion.

The foldings of the pleura form three marginal grooves or recesses :—
1. The pericardio-phrenic groove.
2. The pericardio-sternal pleural reflexion.
3. The costo-phrenic pleural reflexion.

1. *The pericardio-phrenic groove* is a shallow recess formed at the junction of the lower margin of the pericardium with the upper surface of the diaphragm, and lodges the plicæ adiposæ.

2. *The pericardio-sternal pleural reflexion* forms the anterior marginal pleural recess on each side.

3. *The costo-phrenic pleural reflexion* must be considered in greater detail, since it has such intimate relationships with the diaphragm, and plays such an important part in facilitating the movements of the latter. This reflexion is formed by the meeting of the costal and diaphragmatic portions of the pleura. Beginning at the lower border of the sixth rib, close to the termination of the gladiolus, it passes anteriorly downwards and outwards, reaching the point of junction of cartilage and bone of the seventh rib; laterally it descends over the eighth rib to reach the lower border of the ninth in the mid-axillary line, the upper border of the tenth in the posterior axillary line on the right side, and the lower border of the tenth rib on the left side; posteriorly it crosses the eleventh rib, this being its lowest point: ascending slightly, it passes over the twelfth rib, and reaches the lateral aspect of the spine at the lower border of the twelfth thoracic veretebra or transverse process of the first lumbar vertebra below the attachment of the twelfth rib, being separated from the pleura of the opposite side by the posterior mediastinum. Its upper boundary, although in reality varying with the advance and recession of the lower lung margin, for practical measurement of the depth of the reflexion may be regarded as the limit to which the lung descends with each ordinary inspiration. At this level, owing to the difference in the amount of friction between that portion of the diaphragmatic pleura in contact with the visceral layer investing the basal aspect of the lung and the portion in contact with the parietal layer covering the chest-wall, a line of demarcation, indistinct in the young child, but increasingly definite with advancing age, gradually forms, and in middle life becomes very noticeable. This line is best seen on the recent diaphragmatic pleural surface, and, if evidences of old or new pleurisy are present, not infrequently a definite ridge of organised lymph, concave on its upper surface, will delimit the lower lung margin, forming a groove into which the lung fits. The lower margin of the reflexion is wavy or festooned, the festoons being in relation

with the intercostal spaces. In quiet expiration there is an interval of from about 7 to 9 centimetres between the lower margin of the lung and the depth of the pleural recess, whilst in inspiration the lower margin of the lung descends for a distance of 4 cm. or less. In a series of twenty male and female subjects, of ages varying from eighteen to fifty-six, who had died from injuries or diseases not involving the lungs, the average depth of the costo-phrenic reflexion, measured from lower margin of lung to bottom of pleural cavity in the mid-axillary line, on the right side was found to be 8·62 cm. and on the left side 8·34 cm. The greatest interval in the series was 11 cm. on the right side (corresponding to 9 cm. on the left), and the smallest 5 cm. on the left side (corresponding to 6 cm. on the right). In a female infant aged three months the depth of the reflexion post-mortem on the right was 1·5 cm., and on the left 1·4 cm. Ordinarily, the costo-phrenic reflexion, for a distance of from 3 to 5 cm., is not encroached upon by lung at all. Below the level of the reflexion the diaphragm is covered by a strong fascial band, the phrenico-pleural fascia, which passes from the diaphragm and costal cartilages to be attached to the costal pleura so as to hold it firmly in place. The diaphragmatic pleura is thin, whilst the costal pleura is thick: it is intimately adherent to the subjacent muscle, whilst the costal pleura is less firmly bound to the ribs. It is composed of two layers, the one superficial, made up of flat, endothelial cells; the other deep, with rich network of elastic fibres. The costal pleura is similar in structure, save that elastic fibres are fewer.

Function of the Costo-phrenic Pleural Reflexion.

The more or less vertically-disposed part of the diaphragm, which lies beneath that part of the diaphragmatic pleura whose surface is applied to the costal pleura, is, as it were, firmly bound to the chest-wall. The two serous surfaces, which constitute the pleural reflexion, remain in close apposition for a distance varying with inspiration and expiration, and are not separated from each other until the wedge-shaped lower margin of lung glides downwards in inspiration and insinuates itself between them. As the lung recedes the surfaces come together again. In ordinary respiration only the upper half or less of this potential space is utilised: in deepest respiration about three-quarters of it is filled. From conclusions based on numerous experiments I believe that, during life, even in deepest inspiration, the lung does not fill the posterior and lateral portions of this groove which are concerned in diaphragmatic action, the uninhabited portion being necessary to assist the contraction of the diaphragm. That no separation of these two pleural surfaces can take place under ordinary

conditions, except by downward movement of the sharp lung edge, is clear if we regard the local physical conditions. Although, by means of the intrapulmonary atmospheric pressure, the lungs are kept in contact with the surrounding tissues, yet upon these, by virtue of their elasticity, the lungs continually exercise a suction which is negative. Thus, as Leyden has shown, the intrapleural pressure is also negative, and, during deep inspiration, may fall as low as -42 mm. of mercury. Under ordinary conditions the intra-abdominal pressure is positive. This therefore, together with the pressure within the lungs, which is only slightly less than that of the atmosphere, causes both lungs and liver closely to be approximated to the thoracic wall, and consequently to maintain in apposition the contiguous pleural walls which form the costo-phrenic reflexion.

The Significance of the Costo-phrenic Pleural Reflexion.

The significance of the structure of the diaphragmatic pleura, and the disposition of the phrenico-pleural fascia, are at once apparent on consideration of the action of the diaphragm. When the circumferential muscle-fibres contract from the base of the thorax, each fibre necessarily shortens. Owing to the elasticity of the diaphragmatic pleura, this latter is enabled to accommodate itself to the new conditions, and its smooth surface allows it to glide easily over the apposed costal layer which is fixed in such wise that it cannot be displaced when the diaphragm contracts. The thin edge of the lung descends for a variable distance over its upper surface. This pleural union, so beautifully arranged, is of sufficient strength to bind the diaphragm closely to the chest-wall, and is furthermore of mechanical advantage to the diaphragm, since in function it resembles the band or loop through which a muscle acts in order to change the direction of its line of force. Additional evidence in support of this view is supplied by the fact that, whereas adhesions are found post-mortem with exceeding frequency between the two layers of pleura which overlap the lung, they are absent below the line on the pleura above referred to, which marks the lower limit of ordinary travel of the lung.

That the diaphragm peels itself off the chest-wall, as it is said to do, according to the popular explanation of Litten's phenomenon, and so causes the visible shadow-wave, is incorrect. It cannot thus act, for the sum of the forces acting on the apposed surfaces of the costo-phrenic reflexion is too great for them to do anything else than cohere until separated by the advancing lung. I venture to think that the shadow which descends with inspiration is due to the progressively lessening intrapleural pressure during inspiration, which allows the intercostal spaces corresponding to the

apposed pleural surfaces just in front of the advancing lung margin to be driven inwards by the external atmospheric pressure.

VIII. Age-Changes in Thorax and Diaphragm.

Figs. 7 and 8 respectively represent the shape of the thorax and diaphragm in median transverse section in the fœtus and in the adult. The costo-phrenic pleural reflexion, wide and shallow in the fœtus, is narrow and deep in the adult. The fœtal thorax represents the inspiratory type with highly-arched diaphragm: the thorax being short and broad, and the diaphragm exhibiting a uniformly arched surface from front to back and from side to side, the central tendon occupying the highest level. As infancy merges into childhood, under the influence of growth, the thorax gradually changes its shape, and in young people becomes longer and

FIG. 7.   FIG. 8.   FIG. 9.

narrower, as does also the diaphragm, which stands at a level which is relatively lower, but still well above the meso-metasternal plane. The chest, falling inwards during youth and adult life, becomes relatively narrower than that of the child, especially in its lower half, and the pleural recess much deeper.

Coincidently with these age-changes in the thorax inducing lateral compression, the heart progressively increases in weight until the stage of full development is reached, and these two factors, acting simultaneously, cause the diaphragm to sag in the middle, and the central tendon to sink lower than the domes (fig. 9), so that after childhood it is infrequent to find the central tendon reaching as high as the domes.

Along with these changes, too, the diaphragmatic surface of the lung progressively decreases in extent from birth till death, the more rapid diminution occurring between the ages of five and twenty-five, and the most rapid between the ages of ten and twelve. If the total superficies of the lung be represented by 100, at birth the basal or diaphragmatic area constitutes about 25 per cent. of this; by the age of 25 it will have fallen

to about 15 per cent.; from this onwards it may remain stationary, or even further decrease (*vide* figs. 10 and 11).

With each decade of life the diaphragm becomes functionally less active, and this fact, as seen above, corresponds with decrease in size of the base of the lung in contact with it. Does this mean that the diaphragm in man is becoming morphologically less active? The fœtal type of diaphragm is the one which is present in anthropoid apes, as well as in uncivilised races, the crura, in both cases, being strongly developed. Remembering that, as Keith has shown, the primary function of the diaphragm is to pump blood into the heart, and that its participation in respiration is but secondary, it seems
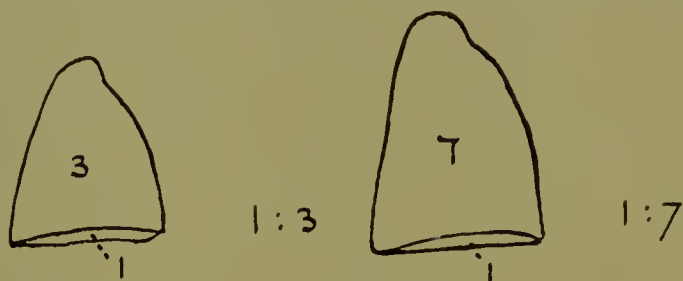
Fig. 10.—The lung at birth.   Fig. 11.—The lung at the age of 25.
(Diagrammatic.)   (Diagrammatic.) ,

reasonable to suppose that civilisation, involving, as it does, a more sedentary and less athletic existence than uncivilisation, is the chief cause of the lessened scope of the diaphragm's activity.

SUMMARY.

In the orthodiagraph we have an instrument whereby we can both observe and measure with exactitude the movements of the internal organs during life. In this paper I have briefly touched upon some of the results obtained. Not only is the orthodiagraph valuable as a means of observing and recording healthy vital processes, but also it can be made of considerable assistance in the diagnosis of pathological conditions. The results obtained by the use of other methods have reference to points which previously have received but scanty attention.